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X-RAY EVIDENCE FOR CAPILLARY PRESSURE DRIVEN FLOW IN PRESERVED CORE FROM THE GEYSERS

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ABSTRACT

Improved understanding of fluid storage and transport mechanisms relevant to The Geysers reservoir is fundamental to efficient and economic long term production of steam. X-ray computed tomographs of core from research borehole SB-15D made within 72 hours of drilling show characteristic x-ray attenuation profiles that can only be explained by imbibition of drilling fluid at reservoir conditions. The shape of the profile is highly diagnostic. Early time scans, when interpreted taking into account independent measurements of pore size distribution, permeabilities and capillary pressures for the rock matrix sampled by SB-15D, are consistent with strong capillary suctions for the recovered rocks. This indirect indication of imbibition under reservoir conditions, along with detailed analysis of x-ray attenuation in recovered core, suggests that water content was low in much of the preserved core. These measurements are part of a series of laboratory experiments monitored by x-ray methods intended to evaluate movement of various fluids to determine the relative importance of capillarity, Darcy flow and vapor phase diffusion.

INTRODUCTION

Approximately 800 ft of continuous core was recovered from borehole SB-15D in The Geysers geothermal field. The DOE drilling operation sampled an area with a long production history and was completed in September 1994. Sections of core were collected at 50 ft intervals and preserved in capped aluminum tubes to minimize drying and disturbance of the core. Prompt x-ray scans of the jacketed, preserved core were made within 72 hours of drilling to improve understanding of water content, storage and distribution in the geothermal field. Determining hydrologic properties was a principal goal of the drilling program. Water content and distribution is necessary input for predictions of reservoir performance and lifetime and for calibrating geophysical indicators of pore fluid distribution in the field.

The principal focus of this paper is a discussion of new interpretations of x-ray scans made within 72 hours of core recovery from SB-15D. The early time scans, when compared with scans made when core is either air dry or nearly saturated, show shapes characteristic of imbitition caused by capillary suction, which is strongest for low water contents. Taking into account independent measurements of pore size distribution, capillary suction for metagraywacke (Persoff and Hulen, 1996) and NMR measurements of water content in selected plugs (Withjack and Durham, 1995), it appears that water content was low in the core preserved at 50 ft. intervals.

Experimental Methods and Procedure

X-ray attenuation images are produced by a specialized industrial scanning system designed to examine high density objects. This tomographic imaging system has several advantages over systems typically used for studies of oil reservoir rocks which are often adapted from medical application. These include higher energy x-rays, better spatial and contrast resolution, and specialized reconstruction software, which directly reconstructs images of a 3D volume. However, scans require long data collections times, ranging from 4 to 8 hours to achieve the spatial and contrast resolution needed to record the small changes in attenuation associated with water saturation in these low porosity rocks. The scanner uses a cone shaped beam of x-radiation to illuminate the object and a two dimensional detector to collect the transmitted radiation. This data collection system includes a CCD camera, coupled to a scintillation detector. A rotational stage is used for obtaining third generation (rotation-only) scans -- 2D radiographs are acquired at each rotational angle, and reconstructed into a volume element. A 450 kVp x-ray machine is the source of penetrating radiation, which is approximately three times higher energy than in a typical medical scanner. Spatial resolution for the images presented here (140 micrometers) is approximately ten times better than for typical medical scanners Contrast sensitivity of this scanner was measured at 0.2% with aluminum penetrameters. Processing and reconstruction software were developed at LLNL. Further details of the scanner hardware and capabilities are given by Roberts et al., 1996, and in the references provided in that paper.

Since the interpretations made here depend on relatively subtle differences in x-ray attenuation, particular attention was paid to the image distortion caused by beam hardening. As the beam passes through the sample, low energy components of the penetrating beam are preferentially attenuated. This effect is unavoidable for polychromatic sources, and produces a characteristic cupping of the image if no correction is made. An aluminum phantom with a diameter of approximately 400 mm was used to determine the hardening correction, which is less severe at the high energies used for these images. The aluminum coring tube, which is ~2.5 mm thick, 'prehardens' the beam which also reduces the image distortion caused by beam hardening. The most convincing argument for the effectiveness of the correction is that both air and nearly saturated whole core samples, also imaged in coring tubes, do not show cupping of the image.

It was critical that all prompt scanning was done while samples were still in the aluminum coring tubes. The expectation was that disturbance of the fluid redistribution by capillary forces would be minimized by prompt scanning, and that fluid loss from slow leaks would be avoided. It also appears that fluid loss from depressurization during core recovery was minimal. Subsequent measurements involving drying and resaturation of whole core have demonstrated that it is difficult to prevent drying of the core and maintain water content near the edges. Carefully preserved core was essential for reliable measurements.

RESULTS AND DISCUSSION

All of the data reported here are images or plots showing x-ray attenuation, relative to air. Radial reconstructions though cores at a range of depths, previously described by Bonner et al., 1995, are presented here in Figure 1. Beginning from the upper left and proceeding from left to right and top to bottom, scan depths are 875, 918, 1420 and 1530 ft. All were recorded within 72 hours of drilling. These images are negatives, with darker areas indicating higher attenuation and density. The thin ring around the core is the aluminum coring tube. The corresponding profiles span approximately a core diameter, which equals ~ 3.4 in. All of these profiles have, to some degree, characteristic higher x-ray attenuation near the core edges, although the details are clearly sample dependent. High attenuation near the core edges is consistent with fluid intrusion during drilling, and cannot be explained by any other plausible mechanism.

The 1530 ft profile also shows high attenuation near the center, a region crossed by a partially filled vein. This porous region clearly appears in the three dimensional reconstruction shown by Bonner et al., 1995 as Figure 4, and probably connects to the core surface and therefore may be an alternate path for imbibition of drilling fluid.

The characteristic profile shape seen in prompt scans (Figure 2a) is lost when core is dried slowly for a period of several weeks, as demonstrated in a scan taken of a slightly different section of the 918 ft core. A scan of the core dried to ambient humidity (~ 30%), implying a low but non zero water content, is shown as Figure 2b. The left side of the profile is typical for the dry case, showing constant or decreasing attenuation near the core edge. The right side is unusual showing a step change associated with a fracture--the sudden drop in attenuation--and change in lithology. The last profile, Figure 2c, was taken close by after the sample was backfilled with water following vacuum evacuation. Saturation in this case was probably greater than 90%. The profile shown is characteristic of the backfilled sample. The attenuation has become higher on average (Roberts et al., 1996), but more importantly for comparison with the prompt scans, shows a decrease near the edges of the core. Although the core was transferred from the water-filled saturation vessel to the aluminum core tube within seconds and the tube was immediately sealed with excess water to saturate the air in the tube with water vapor before the scan, the sample edges dried as the sample reached equilibrium with the small volume of under saturated vapor in the tube. It is particularly significant to note that this did not occur at the drill site because air trapped in the sealing operation saturated with water vapor as the core cooled from reservoir to ambient temperature in the sealed tube. Core preservation methods employed in the field generally prevented dryout (Hulen and Nielson, 1994), and made it possible to observe profiles indicative of mud intrusion.

Quantitative comparisons of the prompt scan with subsequent profiles made before and after water backfilling is difficult because of the heterogeneous lithology and porosity of the core from 918 ft. Nonetheless it is useful to note that the difference in attenuation between the outer and inner regions of the core from the early time scans are a large fraction of the difference between the air dry and backfilled scans, suggesting that a large proportion of the pore space was filled by mud infiltration during drilling.

Independent evidence supports this hypothesis. Mercury porosimetry shows that many rocks from The Geysers have significant porosity in the range below 10 micrometers. Since capillary suction varies inversely with pore size, large capillary suctions are expected. Measurements of capillary pressure by Persoff and Hulen, 1996, for SB-15D graywacke shows that suction is large and is highest for low water saturation. Capillary suction is in general a strong nonlinear function of water saturation and can reach very high values for rocks with small diameter pores at low water saturations. Since this appears to be true for representative samples from SB-15D, then the observed early time x-ray attenuation profiles from SB-15D can be explained by mud infiltration into matrix rocks with fine porosity.

Withjack and Durham, 1994, report results of a successful effort to recover pressurized core near the end of coring (runs 69, 1423 ft and 88, 1600 ft) in SB-15D. Core was recovered, and then frozen to maintain water content and analyzed for water content and mud contamination using Nuclear Magnetic Resonance spectroscopy and a tritium tracer. Tritium contamination consistent with fluid infiltration was detected and correlated with time of exposure to the drilling fluid for run 69, which was detained downhole for 24 hrs waiting for formation pressure to recover. NMR measurements for plugs from the center of core from run 88 which was recovered rapidly showed low water saturations, estimated to be from 3 to 13%. These direct measurements are consistent with high capillary suctions in situ.

CONCLUSIONS

Profiles of x-ray attenuation from promptly scanned preserved core clearly indicate that drilling fluid entered the core at reservoir conditions. However, measurements and indirect indications of matrix permeability in the 10 nanodarcy range for SB-15D metashale and metagraywacke (Persoff and Hulen, 1996; Boitnott and Boyd, 1996; and Roberts et al., 1996) demonstrate that pressure driven Darcy flow cannot account for mud infiltration during the limited time core is exposed to pressurized mud at depth. The most likely explanation for the fluid transport observed in the CT scans is that capillary suction causes the observed fluid transport.

X-ray CT results provide indirect evidence that low water saturations occur throughout the cored interval in SB-15D. Attenuation profiles characteristic of imbibition of drilling fluid occur to some degree in all of the prompt scans of preserved core, suggesting that strong capillary suctions consistent with low saturations are common in rocks collected from an area in The Geysers with a long production history.

ACKNOWLEDGMENTS

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FIGURES

Figure 1 a-d. Radial scans reconstructed for preserved core within 72 hours of drilling; negative images are presented here for improved reproduction, darker areas indicate high attenuation. Scan depths are 875, 918, 1420 and 1530 ft.

Figure 2 a-d. x-ray attenuation profiles across each of the images shown in the previous figure, showing the characteristic shape indicative of fluid infiltration. Local spikes are caused by filled veins. Decreases in attenuation near the core edges for the deepest sample, d), suggest that some fluid was lost to drying prior to the scan.

Figure 3 a, b, c. Attenuation profiles for the 918 ft samples, after drilling (a), equillibrated with ambient humidity (b) and after backfilling with tap water (c).

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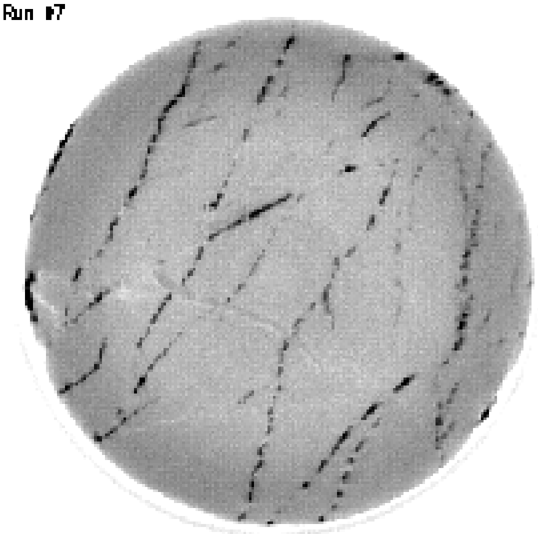

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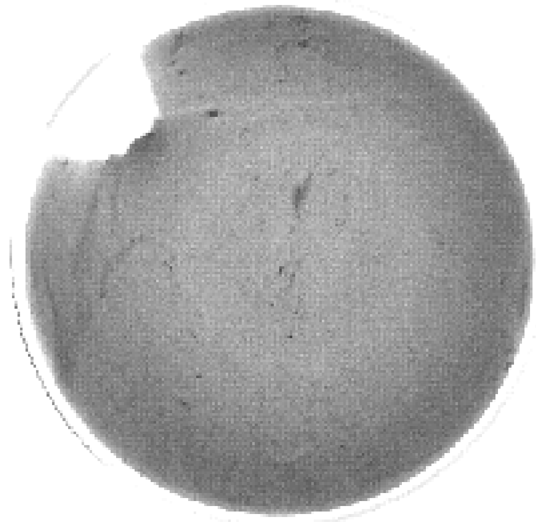

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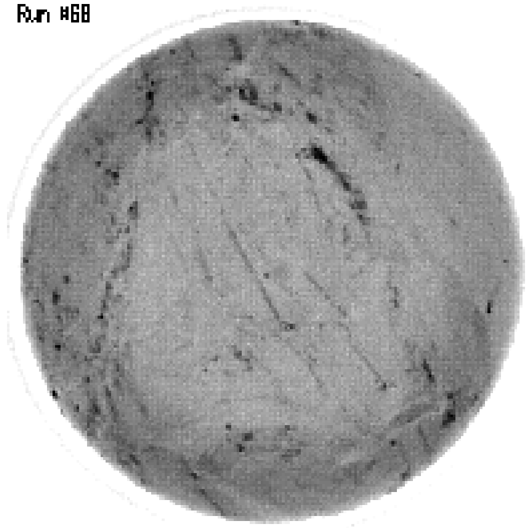

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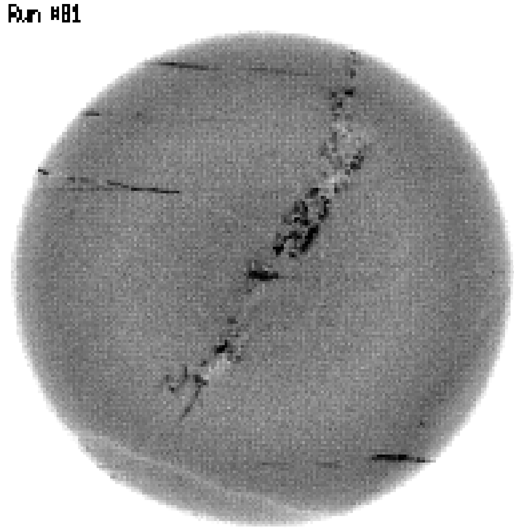

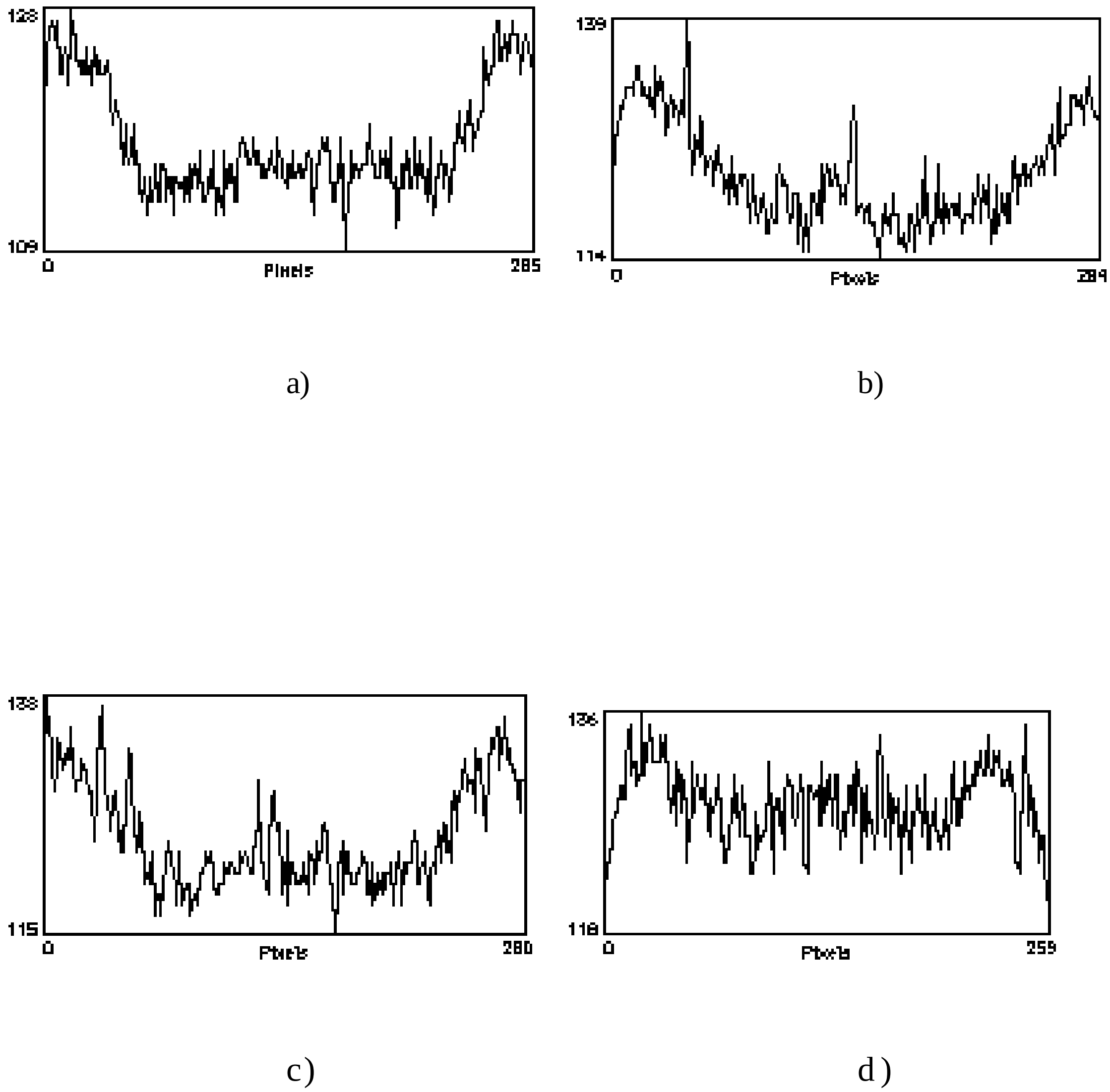

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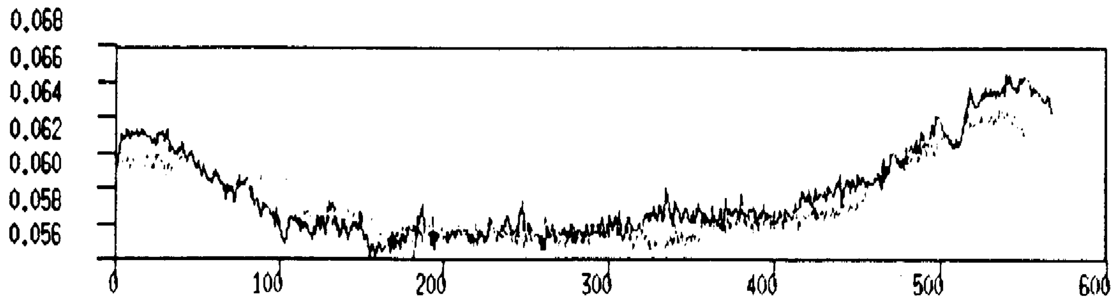
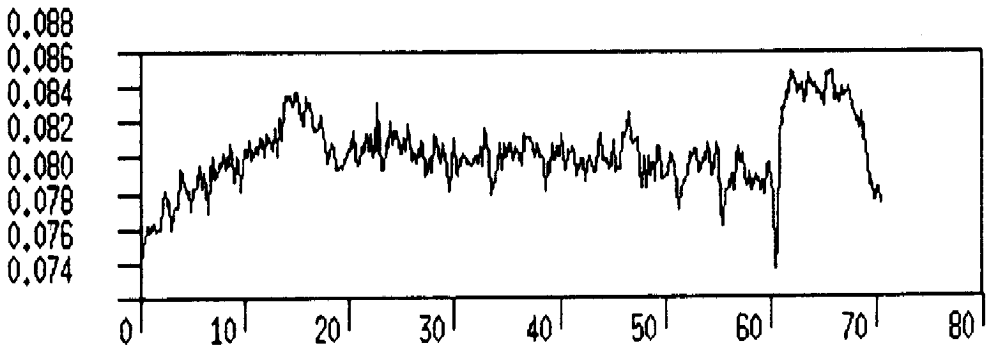


a)



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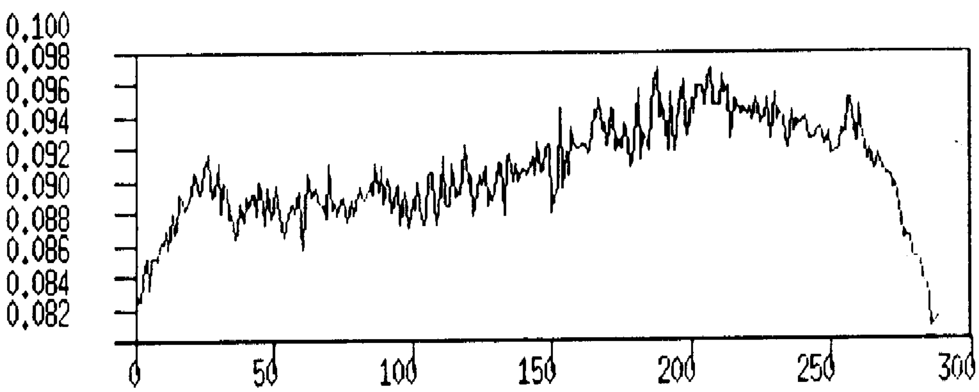

c)

Figure 2a, b, c. Attenuation profiles for the 918 ft samples, after drilling (a), equillibrated with ambient humidity (b) and after backfilling with tap water (c).